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High-performance Ultrafast Photodetectors

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Abstract— **We report spectral and high-speed measurement results on resonant cavity enhanced (RCE) Schottky photodiodes. The Schottky metal contact is semi-transparent and provides the top mirror reflectivity. We demonstrated by simulations that the detector responsivity can be optimized by using a dielectric coating on top of the metal contact. The novel concept of combining a dielectric impedance matching layer with the semi-transparent metal mirror drastically improves the expected quantum efficiency of RCE Schottky photodiodes. Simulations in GaAs/InGaAs material system predicted more than 70% quantum efficiency for an absorbing region of 0.13μm. The devices were fabricated by using a microwave-compatible process. On-wafer high-speed measurements yielded a 18 ps pulse width corresponding to a 3-dB bandwidth of 20 GHz. We also report on our efforts on polarization sensing photodetectors.**

I. Technical Objectives and General Approach

This project concentrates on the design, fabrication and characterization of compound semiconductor photodetectors in various material systems operating at near-IR to UV wavelengths. We utilize resonant cavity enhanced (RCE) detection scheme to optimize speed and responsivity of photodetectors. It is also desirable to combine multiple functions in a single photodetector structure. In addition to wavelength selectivity of RCE photodetectors, we have recently demonstrated that RCE detectors vertically integrated with one-pass detectors can be used for polarization sensing.

II. RCE Schottky Photodiodes

Schottky photodiodes (PD) are very attractive for high-speed photodetection, since they have a simple material structure and fabrication thus allowing for easy integration with III-V discrete devices and integrated circuits. With the increasing demand for faster detector speeds, the optimized structure of a Schottky PD typically has a very thin absorption region. For front illuminated devices, a very thin Schottky metal is used so that light can penetrate the semi-transparent contact and reach the semiconductor. The resonant cavity enhanced (RCE) detection scheme is particularly attractive for Schottky type photodetectors since a semi-transparent contact can function also as the top reflector. RCE detectors with single layer top mirrors are very desirable for post-growth adjustment of the resonant wavelength by simply recessing the top layer. We present theoretical and experimental results on spectral and high-speed properties of RCE Schottky photodiodes with semi-transparent top metal contacts.

We studied RCE Schottky diodes in GaAs/InGaAs material system operating at 900 nm wavelength. Similar principles apply to other III-V materials and different wavelength regions. The devices were grown on GaAs substrates by molecular beam epitaxy. The absorption layer is InGaAs with an In mole fraction less than 10% and a thickness of 130 nm to eliminate the standing wave effect in the cavity. The position of the absorption layer in the depletion region is optimized to yield minimum transit time for electrons and holes. The resonant cavity is formed by a GaAs/AlAs DBR bottom reflector and the semi-transparent Au contact on top. After the Schottky metal, a top dielectric layer (Si_3N_4) is deposited. This matching layer is critical in the optimization of the optical responsivity. We consider only a single layer dielectric coating to maintain simple device fabrication.

We analyzed the dependence of responsivity on the thicknesses of the metal contact (t_m) and the dielectric coating (t_d). By simulations, we demonstrated that these thicknesses can be optimized to yield nearly 75% quantum efficiency at resonance for this thin absorption region. Figure 1 illustrates the results of these simulations showing the variation of peak resonant quantum efficiency with the metal thickness. Without a dielectric coating, the optimum Au thickness is about 150 Å. For different dielectric top coatings (Si_3N_4) serving as impedance matching layers, the optimized Au layer thickness can cover a range from 150 Å to over 300 Å. The capability to use thicker Schottky metal reduces the spreading resistance. To emphasize the advantage of RCE detection, in Fig. 1, we also plot the quantum efficiencies of an optimized RCE Schottky PD and a conventional (one-pass) detector with identical absorption layer and metal thickness. Using the simulation results, the experimental devices have been designed for 900 nm and fabricated with 200 Å Schottky Au and 1250 Å Si_3N_4 top dielectric layer.

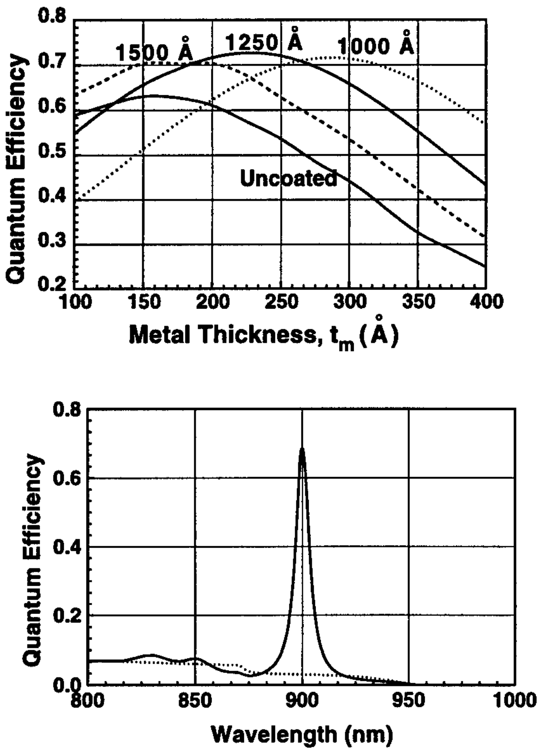

Fig. 1. Top: Simulated quantum efficiencies of RCE Schottky photodiodes as a function of Au thickness (t_m) with various top Si_3N_4 coatings (t_d). Bottom: Theoretical comparison of the quantum efficiency of an optimized RCE Schottky PD and a conventional Schottky PD with a thin absorber (dotted line).

Photodiodes of various sizes were fabricated by standard photolithography with mesa isolation and a Au airbridge connecting the top contact to a co-planar transmission line. The resulting devices showed breakdown voltages larger than 12 V. Large mesa devices were used in spectral response measurements using a monochromatic light source. The resonant peak is observed at 895 nm with a resonant enhancement of 6 fold (See Fig. 2). The measured peak quantum efficiency was about 20% which is significantly less than the theoretical value. The discrepancy is due to the red shift in the center wavelength of the bottom DBR mirror resulting in a ~60% bottom reflectivity. Since the spectral range of the pulsed laser source is limited to 900 nm we were unable to study devices fabricated to operate at the peak of the bottom DBR reflectivity. Optimized device structure is expected to yield ~70% quantum efficiency.

High-speed measurements were carried out using 1.5 ps pulses from a mode-locked Ti/Sapphire laser tuned to 895 nm on a microwave probe station with a 50 GHz sampling scope. Figure 3 shows the pulse response

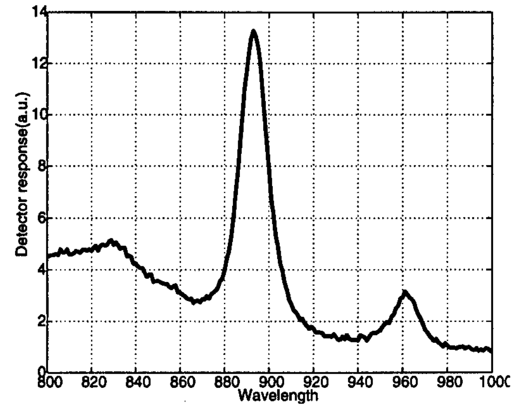

Fig. 2. Experimental spectral response of RCE Schottky photodiodes.

of a $8 \times 9\mu m$ RCE Schottky PD biased at $-2V$. The full-width-at-half-maximum (FWHM) is 18 ps corresponding to a 20 GHz bandwidth. The fall-time of the temporal response is < 15 ps and nearly equal to the rise-time (17 ps) suggesting measurements limited by the instrumentation. By comparison with commercial high speed detectors from New Focus, we estimate the actual FWHM to be around 5 ps. The pulse response shows no tail as expected from the RCE design with the absorption layer placed in the depletion region.

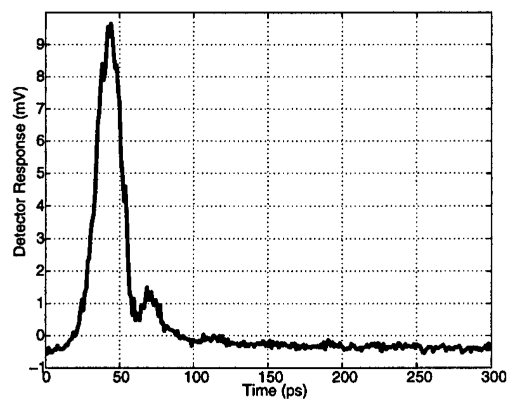

Fig. 3. Measured pulse response of the RCE Schottky PD.

In summary, we have demonstrated a high-speed top illuminated RCE Schottky PD with semi-transparent Au contact. The measured bandwidth of the device is ~20 GHz and estimated speed is in excess of 50 GHz. The optimized structure is expected to yield a bandwidth-efficiency product larger than 50 GHz. A manuscript is being prepared and will be submitted to *IEEE Photonics Technology Letters* [1].

III. Vertical Cavity Polarization Detectors

Establishing polarization selectivity in a compact semiconductor device structure is strongly desirable for many applications, ranging from imaging arrays to magneto-optic data storage. In imaging, there is a compelling motivation to study polarization vision. Potential applications include object recognition, material classification and applications in Marine Biology. Polarization sensing can also be utilized in image enhancing to detect objects otherwise blended in the background. For example, Fig. 4 shows a false color polarized image of a ship on the horizon [2]. Without polarization sensitivity, the ship is blended in the background since both water and the sky are blue. Since the light reflected off the water is strongly polarized, the horizon line and hence the ship is clearly identified. In imaging applications, conventional arrays can be combined with polarizing filters to separate the polarization components either in space or time domain. However, it is desirable to combine the detection and polarization sensitivity functions in the elements of a solid state imaging array.

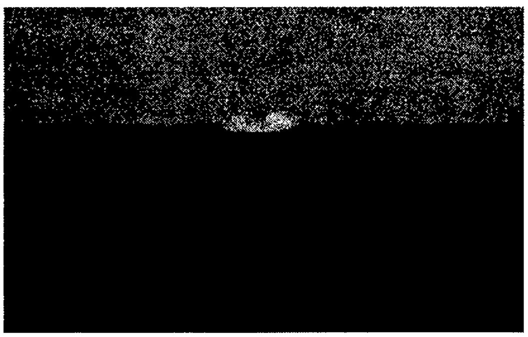

Fig. 4. Grayscale of a polarization image revealing a ship at the horizon. After [2].

In magneto-optical (M-O) drives, the content of the stored data is coded as a change in the polarization of light [3]. The conventional M-O reading head configuration employ polarizing beam splitters and dedicated detectors for the two polarization components. An important drawback of this implementation is having heavy and bulky optical elements which limit the access time. Unlike imaging applications development of discrete polarization detectors will have an immediate impact on M-O storage technology by reducing the weight and complexity of the reading head. The ultimate goal of the proposed work is to build polarization sensitive imaging arrays. The specific short-term task is to prototype the unit cell of these arrays as a discrete device.

We are developing a new method of sensing the linear polarization of light using resonant cavity enhanced (RCE) photodetectors. For off-normal incidence of light, the reflectivity of the semiconductor-air interface can be significantly different for TE (s) and TM (p) polarizations. A polarization sensor can be formed by vertically integrating a conventional and a RCE photodetector as shown in Fig. 5.

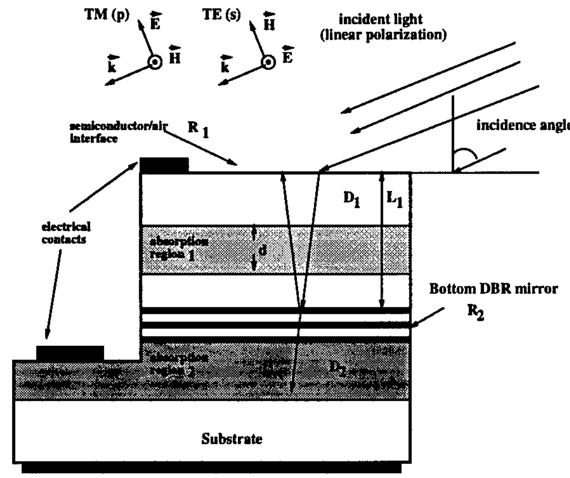

Fig. 5. Conceptual representation of the VCPD consisting of a RCE (D_1), and conventional photodetector (D_2).

Bottom reflector consisting of a DBR structure can be designed to have a large contrast in its reflectivity for the two polarization components. Since the top reflectivity (semiconductor/air interface) is also polarization dependent, the resulting cavity provides resonance enhancement for TE, capturing the TE polarized light in the top detector (D_1). For TM, both reflectivities are small, therefore, light is transmitted to and absorbed in the bottom detector (D_2). For a thin absorbing layer in the RCE detector (D_1 in Fig. 5), a large contrast in TE/TM response of D_1 and D_2 is achieved and the linear polarization can be computed from their relative responses. Figure 6 shows the calculated detector current ratio as a function of the polarization angle for a VCPD formed in the $Si/SiO_2/Si_3N_4$ material system at λ=632.8 nm. Note that there is a one-to-one mapping between the detector current ratio (I_1/I_2) and the polarization angle, and thus polarization can be directly deduced by measuring the ratio of the currents. Since only the relative value of the photocurrent is important and the light is coupled to both detectors through the same window, alignment of the incident light to the detector is not critical.

We have completed the design phase and starting the process of fabricating the detectors on Si. Theoretical results have been published (manuscript submitted prior to this grant) [5]. We have since included this project under the ONR grant. Preliminary experimental results have been presented at LEOS annual meeting [6]. We have completed the design photolithography masks and we are currently using the Si processing facilities at Massachusetts Institute of Technology.

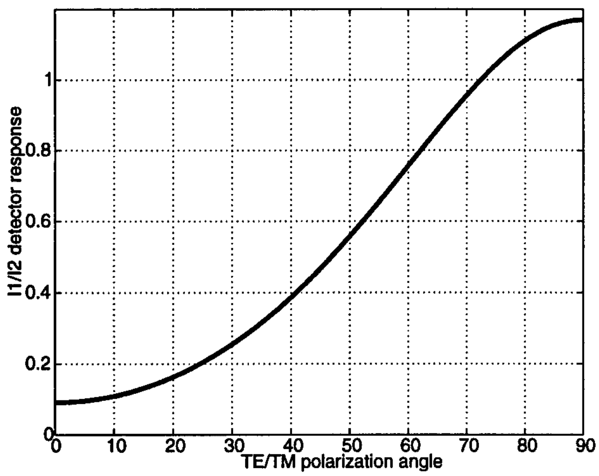

Fig. 6. The ratio of the current responses for detector # 1 and #2 for varying linear polarization angle. The incidence angle is Brewster's angle (for Si/air interface is 73.7°).

The long-term objective of the project is to build polarization sensing imaging arrays on Si substrates monolithically fabricated with VLSI circuits dedicated for on-chip processing of the detector outputs and analyzing the polarization content of the image. The short-term objective is to demonstrate and prototype a discrete device capable of determining the polarization of linearly polarized monochromatic light without requiring critical alignment. These discrete devices will be the building blocks of the imaging arrays. We will also design a M-O reading head utilizing this polarization sensor.

IV. Student Recruitment and Collaborations

Students:

Bora Onat, has completed his MS degree at Boston University with me and now he is continuing for his PhD in Electrical Engineering on high speed RCE photodetectors. I also recruited a new student. Mutlu Gokkavas, completed his MS at Bilkent University on RCE Schottky photodiodes and he has joined Boston University in September 1996 for PhD in Electrical Engineering. I had worked closely with his former advisor and

Collaborations:

NewFocus/Focussed Research: Dr. Robert Marsland of New Focus visited Boston University in July 1996 to discuss the possible collaboration opportunities on high speed RCE devices. We have identified GaAs/AlGaAs RCE detectors at 820-850 nm as the first joint project. The layer structure was designed and grown (provided by New Focus). We are in the process of optimizing the growth parameters.

University of Virginia: Prof. Elias Towe of University of Virginia has been providing us with MBE wafers for RCE Schottky and p-i-n photodiodes. The high-speed Schottky diodes presented above have been fabricated on these wafers.

Bilkent University: As indicated in the original proposal, we are in the process of establishing a strong research collaboration with Prof. Ozbay of Bilkent University. To this end, we have recently obtained an international collaboration grant from NSF. "US-Turkey Cooperative Research: High Performance Resonant Cavity Enhanced Photodetectors and Applications." (INT-9601770). This grant will provide travel expenses for researchers. I visited Bilkent University (supported by United Nations) in July 1996 and the initial results of the collaboration is very encouraging.

Polarization Sensors: We are also collaborating with two Professors at Boston University on the process design (Prof. Scott Dunham) and polarization characterization (Prof. Michael Ruane) for the vertical cavity polarization detectors on Si.

VI. Publications/Patents/Honors/Awards

Within the first four months of this grant, we have prepared one manuscript [1], published a conference paper [6], and one of the students have won a scholarship. Partially supported by the Center for Photonics Research (funded by N00014-93-1-1186), we have bee working on devices proposed under this program prior to the actual start date of the grant. We have filed a patent application [7] on Polarization Detectors and published a journal article [5].

One of the graduate research assistants in this project, Bora Onat, won the 1996 Melles Griot Award in Photonics Research for his work on polariation sensors and EG&G fellowship for work on high-speed and polarization sensing RCE detectors.

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